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14. ABSTRACT

This contract involved a major effort in bringing to maturity, a first-principles theory of semiconductor lasers and amplifiers based on a fully microscopic description of the light semiconductor material coupling. Earlier successes at the microscopic physics level enabled us to obtain quantitative agreement with gain/index and linewidth enhancement spectra measured for a variety of Quantum Well structures. The microscopic studies were extended to materials Iasing at eyesafe and telecoms wavelengths. In particular, in a joint collaboration between Arizona, Marburg and Infineon of Munich, we were able to quantitatively verity gain spectra of novel Nitrogen-doped GaAs and InGaAS materials.

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Semiconductor Amplifiers And Laser Wave Length From Microscopic Physics To Device Applications

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Abstract

This contract involved a major effort in bringing to maturity, a first-principles theory of semiconductor lasers and amplifiers based on a fully microscopic description of the light semiconductor material coupling. Earlier successes at the microscopic physics level enabled us to obtain quantitative agreement with gain/index and linewidth enhancement spectra measured for a variety of Quantum Well structures. The microscopic studies were extended to materials lasing at eyesafe and telecoms wavelengths. In particular, in a joint collaboration between Arizona, Marburg and Infineon of Munich, we were able to quantitatively verify gain spectra of novel Nitrogen-doped GaAs and InGaAS materials. These materials have attracted a lot of attention in the past year as the introduction of a very small percentage of nitrogen I(1% -2%) can reduce the bandgap by a few hundred meV. This is sufficient to move the lasing wavelength into eye-safe and telecoms wavelengths regimes. One important consequence of this discovery is that VCSELs operating at telecoms wavelengths can be fabricated using well-established GaAs DBR mirror technology. The novelty of these Nitrogen-doped materials is that the Nitrogen retains its atomic character in the host crystal and strongly interacts with the conduction band. This feature makes the calculation of gain spectra particularly challenging. A major success of the project was the recent demonstration of a fully predictive characterization of the optical properties of a multiple quantum well (MQW) structure from the materials growth phase through to the final light amplifying device. This work involved a direct collaboration of the ACMS group with the AFRL Materials Growth and Sensors Directorate at WPAFBand Marburg and Bochum Universities in Germany. The MQW structure was grown at WPAFB and on-wafer photoluminescence spectra (PL) measured. The microscopically computed PL spectra were calculated without adjustable parameters and allowed us to give direct feedback to the materials growers at WPAFB on the quality of the MBE-grown active structure. The gain spectra were then calculated and the device was shipped to Bochum University. There the measured gain spectra agreed quantitatively with the calculated gain spectra. This closed the loop in the active device design stage and has stimulated considerable interest from various semiconductor laser

manufacturers and semiconductor software companies.
The simulation model for high power wide aperture semiconductor lasers has been significantly modified to run more efficiently in parallel. The combination of microscopic gain calculations and high power pulsed diode simulation have led to strong interactions with Textron Systems Corp. in the design of a laser profiling system for the Air Force. We have also established close industrial ties with Nortel Networks and have completed some gain spectra calculations for Nortel grown 1.3 μ devices. We are also collaborating with Osram Opto_Semiconductor in Regensburg, Germany on the design of a high brightness vertical-external-cavity semiconductor laser (VECSEL/Optical Disc Lasers). This company used our pre-computed gain tables and our 3D thermal simulations of an optically pumped Optical Disc Laser device, to build a new high brightness device capable of emitting 5-8 Watts CW with an $M^2 < 1.8$ at the highest output power level.

Progress has been made in building a fully interactive platform-independent optoelectronic simulator which should have a major impact on designing sophisticated telecoms and high-bandwidth all-optical sampling systems. We have extended the simulation capability to include classical carrier transport from the contacts into the active layer region of the device. Our aim here is twofold:

1) to interface the electrical/thermal simulation to our existing optical propagation code that is restricted to the active region of the device.
2) To interface the classical carrier transport (drift and diffusion) to the quantum transport within the barriers and active SQW and MQW materials.

The whole package has provided a unique and powerful simulation tool for a wide variety of opto-electronic device and systems simulators, ranging from low power telecoms (edge-emitters and VCSELs) to high power diodes and VECSELs. A preliminary study of incoherent pumping of double clad fibers as potential high brightness sources was also carried out. This has already led to some novel designs to improve the incoherent diode pump coupling efficiency for short length, high gain double-clad fiber amplifiers and lasers. This particular study has allowed us to get a jump-start on the new Multidisciplinary Disciplinary Research Initiativeon "Affordable High Energy Lasers" recently awarded by JTO. This latter project started on July 1, 2002.

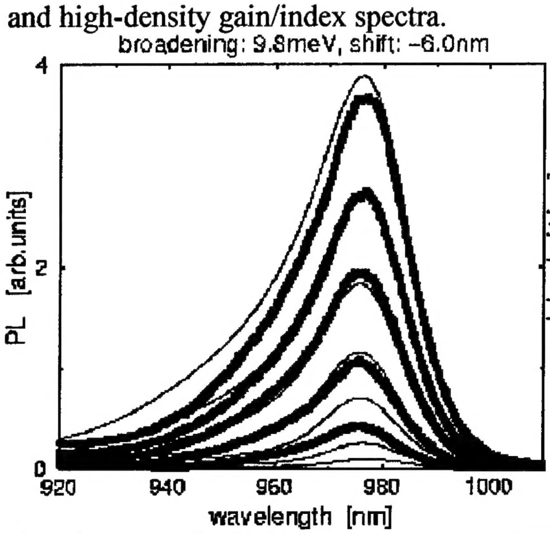
The beginning phase of this contract also allowed us to make progress in explaining the novel creation of an optically turbulent atmospheric light guide. New funding was awarded in June 2000, under contract AFOSR 49620-1-00-0312 to enable us to dedicate our efforts to this important problem. In the following, we highlight significant progress made since the start of this new funding phase.

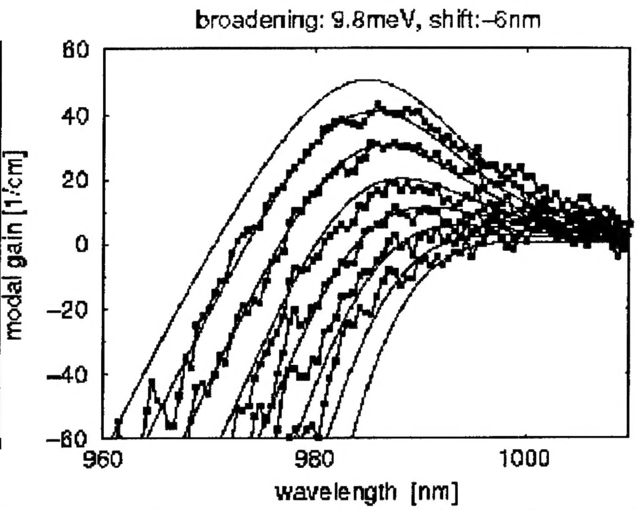
Bandstructure and Microscopic Many-Body Gain Calculations

The recent discovery that a very small percentage of Nitrogen dopant (1% - 2%) can reduce the bandgap of GaAs or InGaAs by a few hundred meV thereby shifting the emission wavelength into the telecoms domain, has stimulated a spurt of activity in investigation of this new material. This material is very attractive for VCSEL structures, for example, because the technology already exists to grow GaAs multi-stack Bragg mirrors whereas InP is not a suitable material. We computed optical gain spectra for this new material and demonstrated quantitative agreement with experimental gain

measurements. The materials were grown and gain spectra measured as part of a collaboration between the University of Marburg and Infineon of Munich. The gain spectra calculations are compute intensive and were enabled by our enhanced supercomputing capability.

A key breakthrough in the past year, allowed us to demonstrate unequivocally that we can now design an active SQW/MQW structure prior to materials growth and provide the grower with a powerful diagnostic tool during the actual growth process. The classical diagnostics to predict ultimate laser performance prior to wafer processing and packaging, are on-wafer photoluminescence (PL) measurements. These can be measured during growth, thereby providing the grower with direct feedback or subsequent to growth on the final wafer. The location of the PL peak is accepted as an indicator of where the final active structure will lase in the running laser. Usually PL-spectra are taken at different illumination intensities on the un-inverted semiconductor material. There has been no *a priori* means of predicting the location of the gain peak in the inverted (higher carrier density) running laser. This project allowed us to develop the microscopic theory to such a level that we can now compute quantitatively reliable PL and gain/refractive index spectra without resorting to the introduction of *ad hoc* fit parameters. We take the same measured bulk bandstructure parameters as are available to the grower and rigorously compute the low-density PL and high-density gain/index spectra.





The picture on the left shows the measured PL spectra in blue and the calculated PL spectra in red for a nominal 3 QW $In_{0.2}Ga_{0.8}As$ structure where the 5 nm wells were separated by GaAs barriers. From the measured data we were able to conclude that MBE growth imperfections were small and that the actual In-concentration was 19% rather than 20%. A small inhomogeneous broadening resulted from growth fluctuations. The PL spectra are shown at increasing illumination intensities from bottom to top. Having determined the uncertainty in the growth, we then computed the gain microscopically and applied the same inhomogeneous broadening of 9.8 meV to the gain curves. These are the red curves shown on the right from bottom to top for increasing carrier density. The device was sent to the University of Bochum in Germany and the gain spectra were measured at different carrier densities. The measured gain spectra are shown in blue on the right and these lie on top of the calculated data. *We emphasize that we were not allowed any adjustable parameters.*

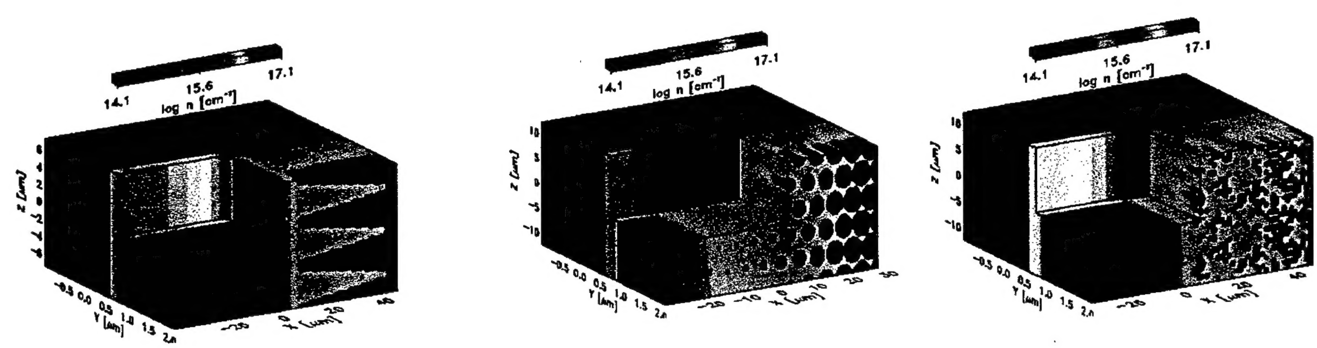
This predictive capability has the potential to revolutionize future semiconductor laser design and provide huge cost savings by avoiding multiple growth cycles and wasteful time-consuming laser packaging. Our work has already attracted global semiconductor laser manufacturing industry

interest (Nortel Networks (Ottawa, Canada), Textron Systems (Wilmington, MA), Osram Opto Semiconductor (Regensburg, Germany) and Infineon (Munich, Germany). We have begun preliminary discussions with RSOFT Inc, a major semiconductor laser software design company, to incorporate our gain tables into their semiconductor laser software package. Other software giants such as Crosslight (Canada) and ISE (Zurich) have expressed a strong interest in having their software incorporate our pre-computed gain tables.

We have also initiated full quantum kinetic calculations in order to evaluate how n- and p-carriers are captured and escape from both SQW and MQW materials. Preliminary results indicate the existence of significant charge inhomogeneity, particularly in narrow MQW materials. This leads to additional gain saturation and will seriously degrade device performance at high modulation rates. As part of this study, we compared carrier capture rates for telecoms GaInAsP, GaInAsAl and GaInNAs materials.

Electrical and Thermal Transport in Diode Lasers

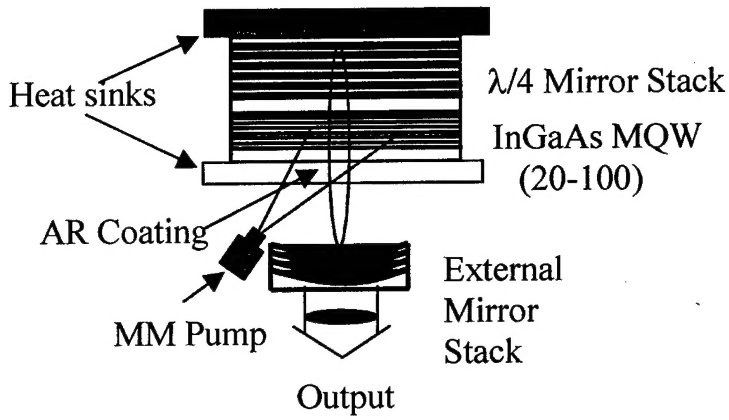
We have developed both 2D and 3D time dependent codes to describe carrier drift and diffusion from arbitrary shaped contacts through the entire structure. These codes are key to understanding how the current enters the active region of a running laser. Our recent efforts carried out in collaboration with the experimental group of J.G. McInerney in Cork, focused on current profiling as a means of reducing intensity filamentation and improving the focusing properties of high power diode devices. In the past we assumed that a fixed current profile was imposed on the active region and were unable to make allowance for feedback from the active layer to the rest of the device. Moreover, we could only guess reasonable current profiles. By coupling the optical propagation to the 3D (or quasi-2D) transport we can now unambigously design the complete device. Our 3D simulation also includes a thermal module that will allow us to design efficient heat-sinking in a running laser.



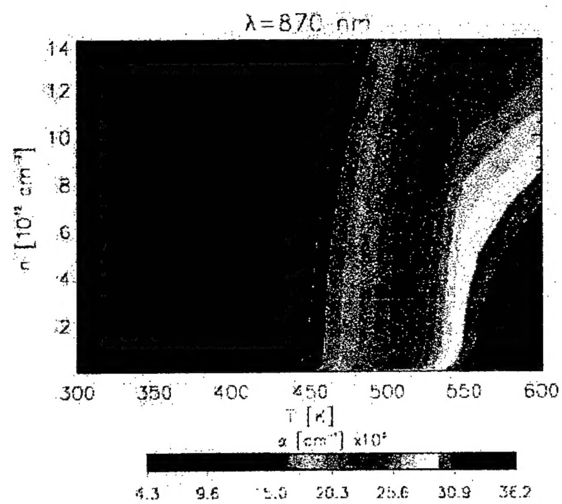
The sequence of pictures above shows three different digitated contact designs for which we were able to compute the current flow into the active layer. Only half of the contact is shown and the light regions on the front face indicate insulating regions. For conventional thickness p-doped layers, there is still strong current non-uniformity, both along and transverse to the device, within the active layer. This non-uniformity reflects the contact geometry because the current cannot diffuse effectively over 3-5 μm p-doped thick layers. Increasing the p-doped layer

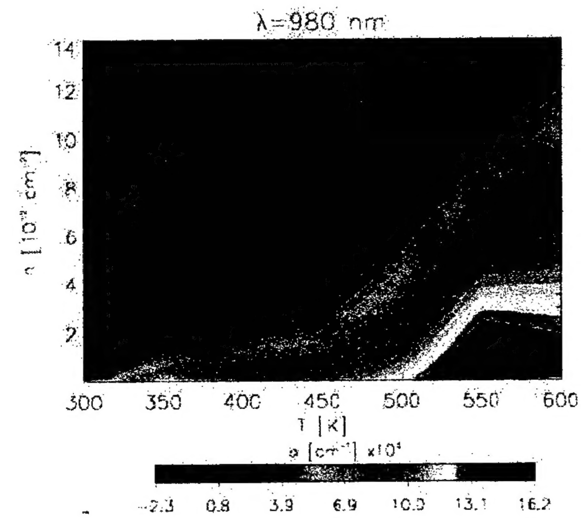
thickness smooths out the current but this increases the electrical resistance and thermal effects within the device. Current and thermal profiles within the active region are input to the optical simulation engine allowing us to optimize a particular device. As an application of this design approach we recently studied the thermal shut-off problem in a high brightness VECSEL structure.

The VECSEL cavity is shown on the right. This particular device is being considered by us as a viable high power, high brightness diode pump source for fiber amplifiers and lasers as part of the MRI project on "Affordable High Energy Lasers". Significant heating in the active region of this structure can cause it to shut-off prematurely. This severely limits the potential for extracted high power. Otherwise this device would be ideal for high power extraction as



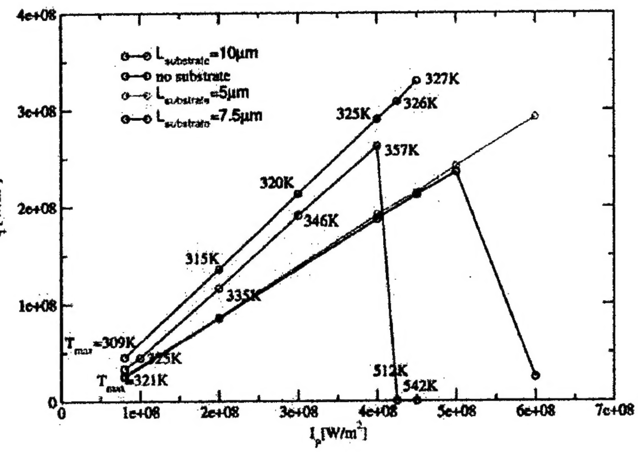
the active region is sufficiently thin to enable efficient heat sinking. Our microscopic gain and index spectra can be pre-computed over a broad 2D landscape of carrier density and temperature variation for a specific MQW active structure. We consider an optically pumped VECSEL cavity where the diode pump beams are incoherent. The full 3D heat transport within the structure can be computed with the pre-computed active material absorption and gain included within the simulation. We consider a 14 QW InGaAs active material with AlGaAs barriers and the multimode pump aligned along the laser axis.





The picture on the left is a contour plot of the absorption landscape for a diode pump laser at a wavelength of 870 nm. The microscopically computed absorption is computed between 300 and 500 °K along the horizontal axis and over a range of sheet carrier densities from $1 \times 10^{12} - 14 \times 10^{12}$ cm^{12} along the vertical axis. The corresponding gain/absorption landscape is shown on the

right at a signal wavelength of 980 nm. This data provides a design space to optimize the VECSEL structure for high power extraction.



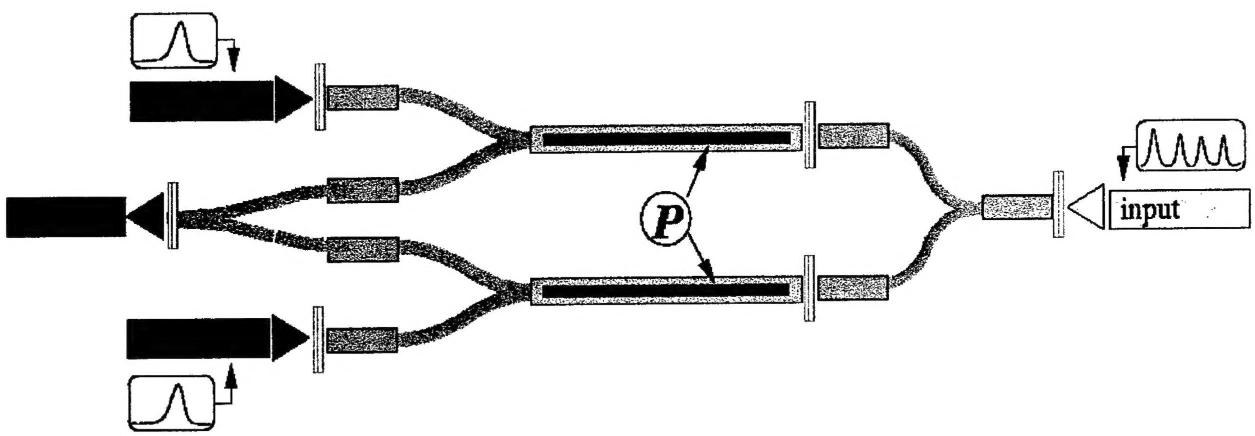
The input-output characteristics on the right show a sequence of L-I characteristics for varying thicknesses of substrate with a copper heatsink placed below the DBR mirror. The numbers along each curve show the computed internal temperature in the active MQW region. As the active region heats up with increasing pump power, the gain shifts strongly and saturates. Consequently one must provide more pump power to generate more carriers to offset the heat-induced saturation. The thicker the substrate, the more difficult it is to extract heat and consequently the device heats up and subsequently switches off. We have been collaborating with Osram Opto Semiconductor to design a specific high power, high brightness VECSEL structure. Our microscopically computed gain/index tables allowed this company to successfully design an operational VECSEL device. We are proposing to pursue this approach to design a high power, high brightness VECSEL pump source as part of our new MRI project.

Interactive Supercomputing-based Simulation Tools for Diode Lasers

This aspect of the project entailed building large bandwidth interactive simulation tools to study two classes of semiconductor laser problem. The first project involved building a platform-independent 1D interactive simulation tool that would allow us to assemble complete integrated optics systems and study how individual components in a network could influence the performance of others. The core of the simulator is written in C^{++}, graphical observers implemented are implemented in TK/TCL, communications functions implemented in CORBA and the external user interface in Python. The core of the simulator includes highly efficient numerical algorithms to advance the optical fields and track the internal carrier density on the fly. These algorithms can resolve the physically relevant gain and refractive index bandwidth of the running device. The second project was geared towards building a similar robust simulation environment to simulate high power diode lasers. The added lateral spatial dimension in this problem adds significantly to the computing requirements and this simulator as built to run in parallel across multiple CPUs in our shared memory ONYX2 Silicon Graphics supercomputer.

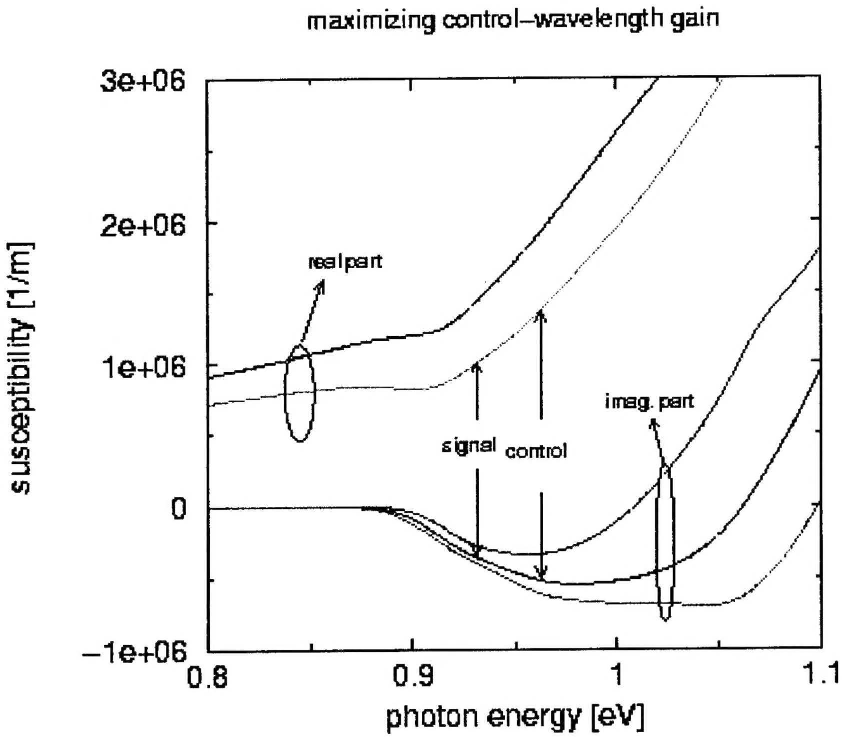
The 3D thermal and electrical transport models discussed above provide pre-computed heat and current distributions within the active layer. In this way, we can incorporate contact digitations and Joule heating (thermal lensing) influences in the optical simulation. The unique aspect of this high power diode simulator is the incorporation of pre-computed gain and index spectra as a function of carrier density and temperature in the device. Strong non-uniformities in these quantities within the active region mean that different local regions within the active layer experience different gain and frequency -pulling effects at a particular instance of time.

An example of a the application of the 1D simulator to a complex integrated optics system is a Mach-Zehnder interferometer with semiconductor optical amplifiers (SOAs) in both arms. This device has been proposed as a high bandwidth all-optical sampling system for various high speed data processing applications including time-division demultiplexing of hundreds of gigabits data streams. The layout of this device is shown in the picture below.

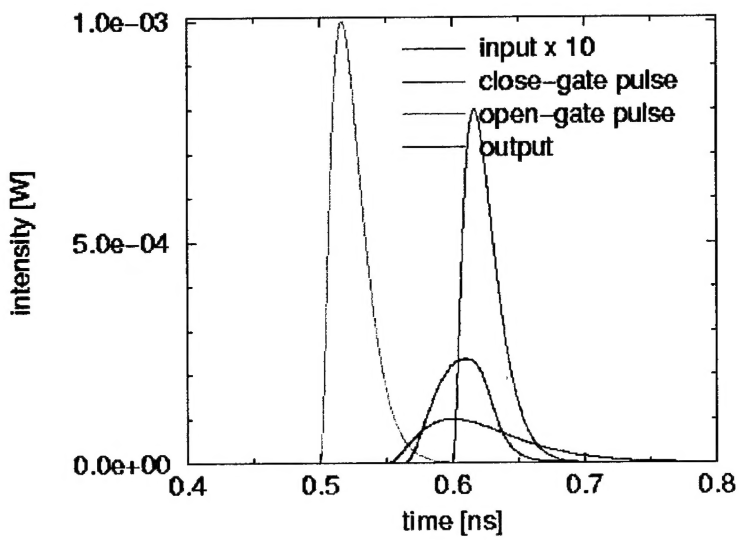


In addition to the interferometer arms, other key components of this data processing element are an input port (yellow) on the left that feeds in a muti-Gigabit data stream consisting of many different, say 10 Gbit, data channels. The interferometer arms are initially mismatched such that no data bits can reach the output port on the right (purple). The SOAs in each arm are indicated in red. The sluggish response of the carriers in a semiconductor amplifier (relaxation oscillation time ≈ 1 nanosecond) means that this data stream cannot be switched by direct modulation of the current of the SOAs. Instead two switching pulse streams are input from separate ports on the left. These pulse streams can be delayed relative to one another by a fixed amount. The first pulse entering the top SOA (gate-open) transiently matches the interferometer arms such that any bit (input pulse) will pass through. The second switching pulse (gate-close) mismatches the arms again and prevents data from passing through. This gate-open gate-close sequence can be extremely fast. The SOAs can be optimized using the microscopically computed gain and index tables – for example one wants the switching pulses to be of low power and see gain within the SOA so as to pull as large as possible a phase (refractive) index change. The input pulse stream (signal) is optimized to see a linear gain within the SOAs.

The figure below shows how the microscopically computed gain and index spectra are used to design an efficient demultiplexor.



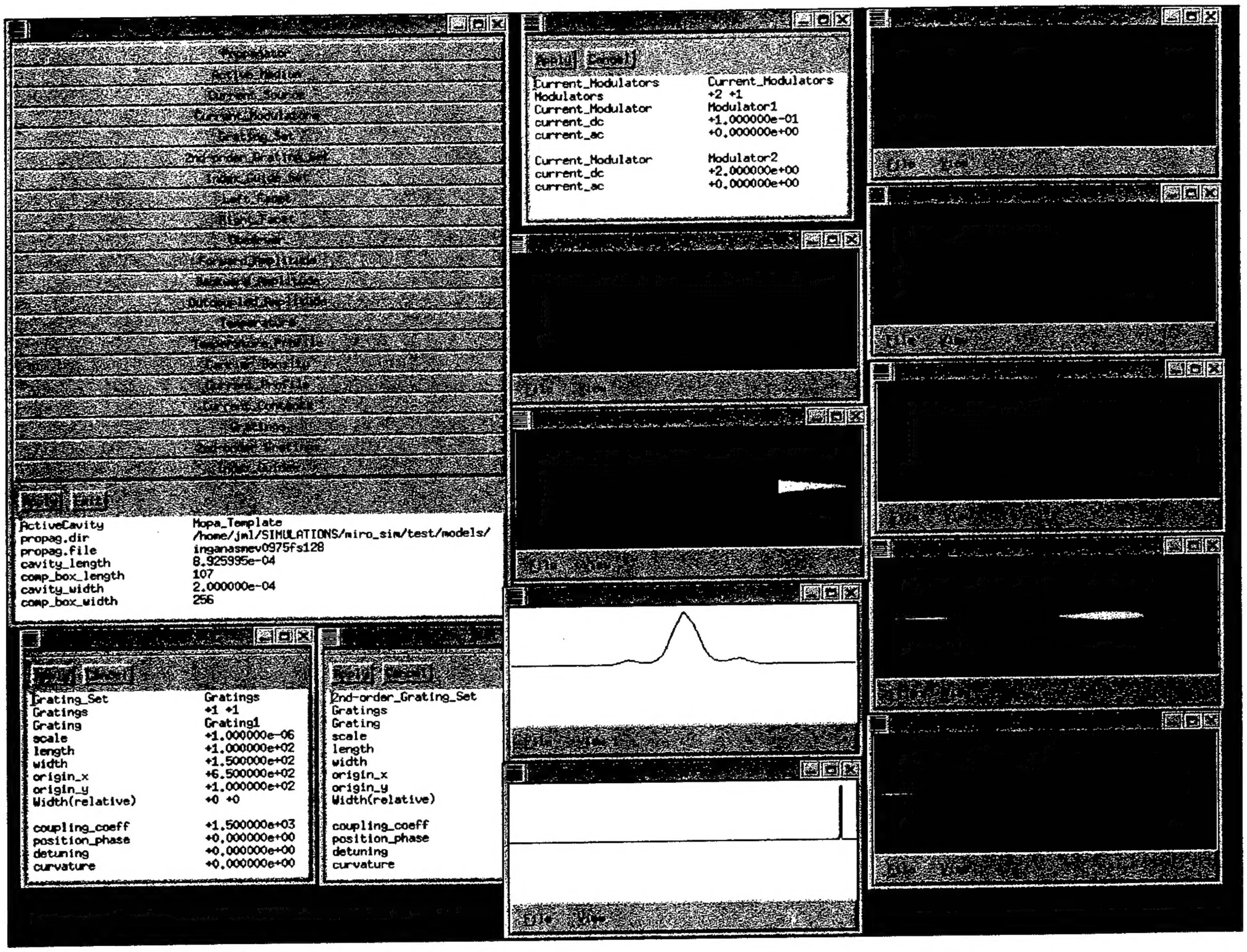
The demultiplexing action is shown in the figure below. The green control pulse opens the gate, the black signal pulse is allowed through and amplified in the SOA (blue) and the red pulse closes the gate. In this manner data streams can be pulled off at fixed time intervals.



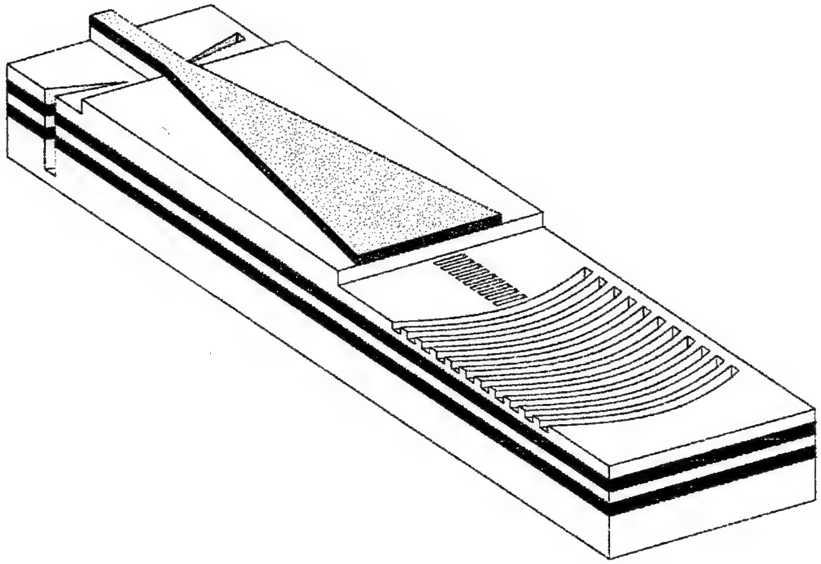
There are many permutations and combinations of components that can effect such complex data sampling actions. The combination of 1D interactive simulator and microscopic gain tables

provides a unique and powerful design tool for building and evaluating such complex integrated switches.

The high power diode simulator provides a higher level of functionality allowing the user to assess the role of filamentation within high power diodes and design strategies to suppress such undesirable features. The simulator has a GUI interface (shown below) allowing the user to interact with and modify the system on-the-fly.



The layout of the GUI interface is shown above. The pull-down menu on the top left allows the user to pop-up and modify critical device parameters during the simulation. In addition, various graphical windows depicting internal optical, carrier and temperature field evolutions, near-field, far-field and spectral outputs can be invoked at will. The simulation depicted above is of a flared MOPA device with a first-order and second-order grating on the right. This device has been fabricated by the group of Professor M. Fallahi (Optical Sciences Center, Arizona) as part of the new MRI project on “Affordable High Energy Lasers”. The actual device is shown below.



The first order grating provides filtered feedback for single wavelength operation and the second order grating provides surface out-coupling. The high power diode simulator is still under development and will play a central role in designing new generations of improved brightness diode pumps for fiber amplifier and laser systems.

Incoherently Pumped Double Clad Fibers

This projected provided further leverage for us to jump-start an effort on high power double clad fibers lasers. Our preliminary work has focused on understanding the basic physics responsible for coupling incoherent pump light from diode bars into a single mode doped fiber core. Early studies indicate that random and weak index perturbations can significantly enhance the coupling over and above that of an idealized homogeneous glass inner cladding. The source of such perturbations may be intrinsic imperfections in the glass itself or induced nonlinear index changes (Kerr or SBS, for example).

High Power Femtosecond Light Strings

The preliminary effort carried out on this project was leveraged by funds provided under the present contract. We extended the adaptive mesh parallel solver to account for vectorial (polarization) effects and were able to obtain some preliminary results in this area.

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